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DETERMINATION OF MINIMUM ADHEREND THICKNESS FOR CLIMBING DRUM AND FLOATING ROLLER ADHESIVE TESTS

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The Climbing Drum Peel Test (ASTM D1718-76) and the Floating Roller Peel Test (ASTM D3167-76) are adhesive joint tests used to determine adhesive strength in honeycomb core tactical shelter panels. The failure modes and geometries of these tests tend to differ from specimen to specimen, however, depending on the ratio of adhesive strength to flexible adherend stiffness. This inconsistency generates peel strength data which cannot be directly compared. Although the problem can be solved by making the flexible adherend very thick so that all failure geometries are alike, the result is a loss in precision in the test results. An analysis of these test methods was performed in order to specify the minimum flexible adherend thicknesses which produce consistent failures. Experiments confirmed these predictions. Parametric studies and experiments indicate that, among the properties examined, glue line thickness and yield strength of the adherend most affect the minimum adherend thickness which can be used. A first order analysis was also conducted in order to "correct" the results of peel tests which do not fail in a "consistent" manner (i.e., the adherends detach from the test fixture rollers).

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Preface

The efforts reported herein were performed by the University of Dayton Research Institute (UDRI), Dayton, Ohio, under Air Force Contract F33615-85-C-5094. The program was sponsored by the Materials Directorate, Wright Laboratory, Wright-Patterson Air Force Base, Ohio. Air Force technical direction was provided by Mr. Frank Fecheck, WL/MLSE, Air Force Project Engineer.

The work was performed during the period November 1988 to October 1990. University of Dayton project supervision was provided by Mr. Dennis Gerdeman, Supervisor, Materials Engineering Division, and Mr. D. Robert Askins, Head, Plastics, Adhesives, and Composites Group. Technical effort was accomplished under Mr. D. Robert Askins as Principal Investigator, with Mr. T. J. Whitney being responsible for analysis and coordination of testing. The author wishes to acknowledge Mr. Dee Pike for specimen fabrication and Mr. Don Byrge for mechanical testing.

NOMENCLATURE

a	= Thickness of bondline
Apparent Peel Strength	= Peel strength calculated without regard to whether the adherend conforms to the roller
b	= Width of the flexible adherend
c	= Half thickness of flexible adherend
CDP	= Climbing Drum Peel
$\bar{E}$	= Energy per unit length to deform skin
$E_{absorbed}$	= Energy required to raise the drum and deform the skin during a CDP test
E_{in}	= Energy input in a CDP test
E_y	= Post-yield modulus of flexible adherend
E_1	= Young's modulus of flexible adherend
E_2	= Young's modulus of adhesive
F	= Force required to run a CDP test
FRP	= Floating Roller Peel
L	= Total length of nonconformed region in FRP test
M	= "Moment arm" in FRP test from the debond point to the line through which the applied load acts
M_x	= Moment produced at any point x on the flexible adherend
m'	= "Moment arm" in FRP test from debond point to a line through which internal forces (free body) act

NOMENCLATURE, continued

M_o	= Moment produced in the flexible adherend at x=0
P	= Load applied at adherend during FRP test
r	= Radius of roller (FRP)
r_a	= Skin radius = Web radius plus 1/2 skin thickness
r_b	= Strap radius = Drum flange radius plus 1/2 strap thickness
S_f	= Distance through which F moves
S_W	= Distance drum is raised
s	= Arc length along flexible adherend in FRP test
$T_{adherend}$	= Torque required to deform adherend and raise drum
True Peel Strength	= Peel strength obtained when adherend conforms to roller
U	= Total strain energy in an FRP test
$\bar{u}$	= Average energy per unit length
u_e	= Strain energy per unit length associated with curvature in the elastically deformed region of FRP adherend
u_p	= Strain energy per unit length associated with curvature in the plastically deformed region of FRP adherend
W	= Weight of drum in CDP test
x	= coordinate, originating at the debond point, along the debonded length of the specimen

NOMENCLATURE, continued

y	= deflection of flexible adherend still bonded to the rigid adherend
y_{max}	= Maximum deflection of unbonded adherend
β	$= \sqrt[4]{\dfrac{3E_2}{8E_1c^3a}}$. A convenient grouping of parameters
ε	= Strain in adhesive layer
θ	= Dummy variable which represents ω in a free body diagram of the adherend
κ	= Curvature of flexible adherend
κ_c	= Curvature of FRP flexible adherend which deforms elastically only
κ_p	= Curvature of FRP flexible adherend which deforms plastically
σ_{max}	= Maximum cleavage stress in adhesive layer
σ_o	= Tensile strength of bulk adhesive
σ_y	= Yield strength of flexible adherend
ω	= Coordinate in FRP test specifying the angle from a line tangent to the point where a nonconforming flexible adherend reattaches to the roller, to a line tangent to a given point on the flexible adherend
$\bar{\omega}$	= Maximum value of ω, occurring at the debond point
ω_c	= Angle at which flexible adherend begins to plastically deform in FRP test

NOMENCLATURE, concluded

Appendix

c	= Flexible adherend thickness
E	= Young's modulus of adhesive
h	= Instantaneous thickness of adhesive layer
h_o	= Initial thickness of adhesive layer
R	= Radius of roller (or drum)
t	= time
u	= Displacement in adhesive layer
V	= Velocity of the peel test (= velocity of adherend midplane)
V_{AD}	= Velocity of the adhesive (= velocity of the adhesive adherend interface)
ε	= Strain in adhesive layer
$\dot{\varepsilon}$	= Strain rate in adhesive layer
ε^u	= Strain to failure of adhesive
θ	= Angle coordinate formed by two radii of the roller. Origin is at the debond point
σ_o	= Tensile strength of adhesive

SECTION 1

INTRODUCTION

Many transportable tactical shelters used by the various military services for a multitude of applications consist of sandwich construction in the walls, floor, and roof. One of the important considerations for this type construction is the strength and durability of the adhesive bond between the sandwich skins and core.

1.1 Background

The Climbing Drum Peel (CDP) Test (ASTM D1781-76) is an adhesive joint test often used to quantitatively measure the strength of adhesives used to bond metal skins to honeycomb core in tactical shelter panels. As shown in Figure 1.1, the test consists of debonding the metal skin from a honeycomb core sandwich specimen in a peeling mode by wrapping the skin around a drum, which proceeds along the length of the specimen during the test. A portion of the load, or torque, required to pull the drum along the length of the specimen, however, actually goes into wrapping the skin around the drum after it has detached from the core. The portion of the total load going into this plastic and permanent deformation of the skin must be accounted for so that reported "peel strengths" precisely represent the torque required to rupture the adhesive bond. The torque to wrap the skin around the drum must either be calculated or measured, and must be subtracted from torques measured for actual bonded specimens. Traditionally this has been measured by fastening a section of unbonded skin material in the fixture as illustrated in Figure 1.1, and running the test to generate a calibration torque. This value is then subtracted from the torque determined in the test of a bonded specimen, with the difference being considered the adhesive peel torque or peel "strength."

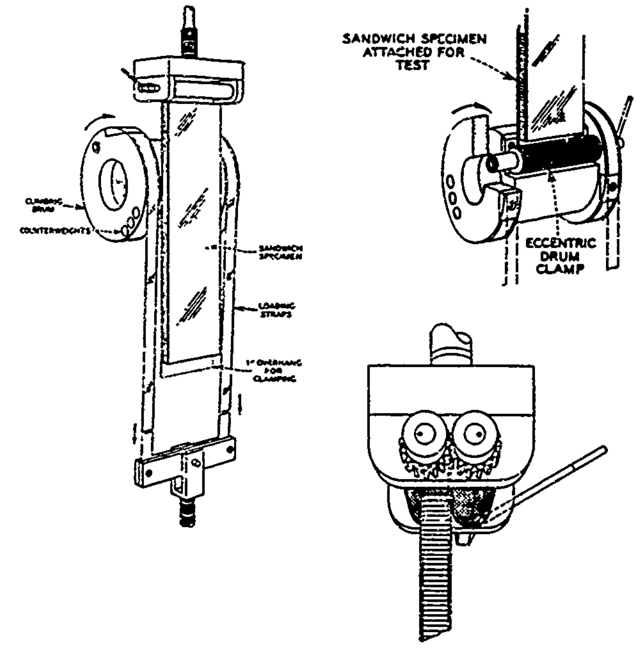


Figure 1.1. Climbing Drum Peel Test (ASTM D1781-76).

In the case of 0.040-inch (1 mm) aluminum skins which are widely used in shelter construction, a load of approximately 100 lb. (45.4 Kg) is required to wrap the skin around the drum and raise the test fixture during the test. This compares to a total load of approximately 130 lb. for bonded honeycomb sandwich panels. Thus, skin deformation and the lifting of the test fixture accounts for around 75% of the total measured load, and the adhesive peel strength is the difference between two relatively large numbers. This is an undesirable situation at best, because a relatively small error in one of the larger measured numbers produces a relatively large error in the difference (the "adhesive peel strength").

For the purposes of generating comparative adhesive properties, D1781 suggests using 0.020-inch (0.5-mm) thick aluminum as the peeling skin material. This is not a thickness typically used in tactical shelter construction. If specimens employing actual skin thicknesses (0.040-0.060-inch, 1-1.5 mm) are tested in CDP, the portion of the total load consumed in plastic deformation of the skin as it wraps around the drum is much larger than it is in the case of 0.020-inch (0.5-mm) skins, leading to much greater susceptibility of the results to error.

In addition to the occasional desire to test specimens with skin thicknesses larger than that suggested in D1781, the skin material (and consequently the stiffness) also varies from application to application. If specimens representative of the actual application are tested, one can encounter wide variations in the relative torque needed to wrap the various types and thicknesses of skin around the drum. The effects of these differences are not thoroughly addressed in D1781.

Reducing skin thickness to reduce potential error also has drawbacks. A skin of insufficient thickness, as it bends around a drum, would not have sufficient stiffness to transfer the load required to fracture the adhesive while remaining conformed to the drum surface. In order to develop the required load, it would have to bend to a greater curvature than that of the drum. This requires the skin to detach slightly from the drum surface which, in turn, would generate higher torques. The "peel strength" computed from such a test would be artificially high, because more torque is required to bend the adherend to this greater curvature than in the calibration specimen. Whether or not this detachment occurs would be a function of the relative strength of the adhesive and the stiffness or rigidity of the skin.

In order to investigate this phenomena, it is instructive to consider a similar test for which the behavior is readily apparent. The Floating Roller Peel (FRP) test (ASTM D3167-76) is another adhesive test which is affected by the thickness (or rigidity) of a flexible "skin." As Figure 1.2 shows, the test consists of pulling a bonded sample, consisting of rigid and flexible "adherends" bonded together by a thin layer of adhesive, through a test fixture containing rollers. The flexible adherend is peeled away from the rigid adherend and wrapped around one of the rollers in a manner somewhat analogous to the situation in a CDP test. Pulling the specimen through the fixture causes an initial crack in the bond to propagate, and the specimen to debond. The force required to fracture the bondline and wrap the flexible adherend around the roller is taken as the "peel strength" of the adhesive. Although not suggested by ASTM D3167-76, the energy to deform the adherend should be taken into account to correctly calculate "peel strength." This is because the adherend deforms plastically as it bends to the radius of the roller. All of the energy is not recovered as the adherend straightens out. The result of failing to account

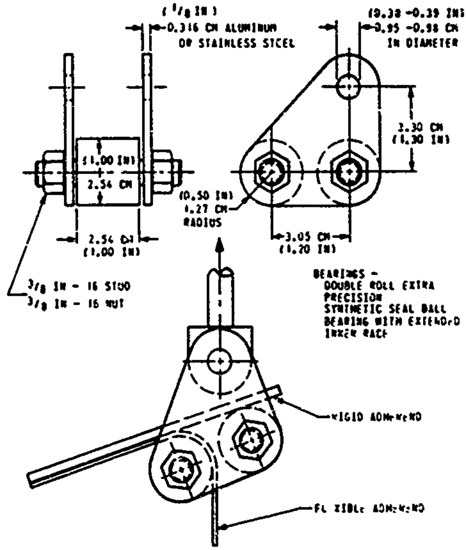


Figure 1.2. Floating Roller Peel Test (ASTM D3167-76).

for the energy required to plastically wrap the flexible adherend around the roller is that the reported adhesive peel strengths are artificially high.

Extreme ratios (high or low) of the flexible adherend stiffness to the adhesive strength cause the FRP test to progress incorrectly (Figures 1.3 and 1.4) since the ratio significantly affects the point at which the adherend detaches from the rigid member and the degree of permanent curvature imposed upon the adherend (a low ratio is analogous to the problem of the adherend in a CDP pulling away from the drum). ASTM D3167-76 states that the angle of peel must be consistent from specimen to specimen if peel strengths are to be compared. This requirement stems from the possibility that should the adherend not conform to the roller as fracture occurs, or if the fracture occurs at various points from test to test, the peel strengths measured may represent different test geometries and different modes of fracture. Even if the fracture modes are similar, the relative energy required for adherend deformation around the roller is either lower or higher (depending on whether the behavior is that illustrated in Figures 1.3 and 1.4, respectively) than that required during a test in which the adherend conforms to the roller. An adherend deformation energy value obtained through testing of an unbonded adherend or through available calculation techniques [1] is valid only for an adherend which *conforms to the roller*. Subtracting this value from the results of actual FRP tests will result in validly corrected peel strengths only if testing of the bonded specimens results in the flexible adherend conforming perfectly to the roller. If, instead, the flexible adherend behavior is as illustrated in either Figures 1.3 or 1.4, the subtraction of the adherend deformation load from the bonded sample load will produce adhesive peel strength values that are artificially lower or higher, respectively, than the true case.

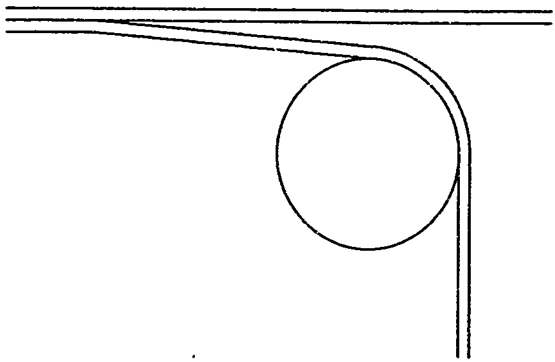


Figure 1.3. High Ratio of Adherend Stiffness to Adhesive Strength in an FRP Test [1].

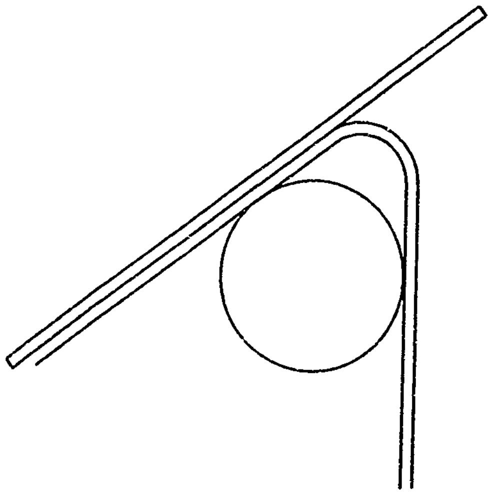


Figure 1.4. Low Ratio of Adherend Stiffness to Adhesive Strength in an FRP Test [1].

A modified FRP test fixture designed by UDRI [1] solved the problem of too high a ratio of adherend stiffness to adhesive strength by adding additional rollers which forced the specimen into a consistent geometry during the test. This UDRI fixture is illustrated in Figure 1.5. The opposing problem of a too low adherend stiffness to adhesive strength ratio could not be solved by further modification of the fixture due to space limitations, and is virtually impossible in the climbing drum peel due to the geometry of the test. The alternative is to choose the thickness of the adherend (based on previously known mechanical properties of the adherend and adhesive) so that detachment always occurs while the adherend conformed to the roller. This would entail an analysis to calculate the minimum thickness required to keep the adherend attached to the roller.

In summary, the approach to preventing apparent skin thickness effects in CDP tests is to solve a problem due to similar "skin thickness" effects in a more general test (FRP) and to specialize the analysis and solution to the CDP test.

1.2 Objectives

The general goals of this program were to suggest methods for eliminating or accounting for the effects of varying skin thickness on CDP and FRP test results. The specific objectives to achieve these goals were as follows:

1. Develop two approaches to solving the problems in the Floating Roller Peel test method

    A. Perform an analysis of the Floating Roller Peel test and develop a methodology for sizing flexible adherend thicknesses so that the peeling adherend

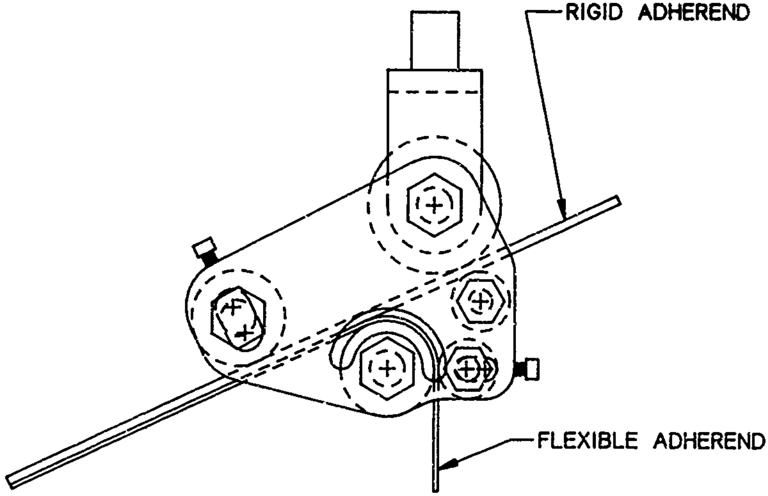


Figure 1.5. UDRI Floating Roller Peel Fixture.

will conform to the roller. Verify the analysis with actual FRP tests.

B. Perform an analysis of the Floating Roller Peel test and develop a methodology to account for the extra energy expended in deforming the adherend if the adherend does not conform to the roller. Verify with actual FRP tests.

2. Extend the analyses of FRP tests to the CDP test.

A. Perform an analysis of the CDP test to calculate the torque required to deform the skin if it conforms to the drum (as was done for the FRP test in [1])

B. Extend the analyses which size adherends and calculate non-conforming adherend energy from FRP tests to CDP tests. Verify the analysis with tests.

SECTION 2
ANALYSIS OF THE FLOATING ROLLER PEEL TEST

2.1 Analysis of Free Peel and Modifications

Kaeble and others [2,3] performed a first order analysis of the free peel phenomenon to calculate the stresses in the bondline between a flexible adherend and a rigid member. That analysis, with some modifications and assumptions, provided the basis for a model to size the flexible adherend so that it would conform to the roller. The basic approach is to assume that the fracture in the adhesive layer will propagate when the cleavage stress (the stress normal to the plane of the test specimen) exceeds the tensile strength of the adhesive. The thickness of a flexible adherend which will produce this stress *as the adherend conforms to the roller* can then be back calculated.

The expression for the cleavage stress in the bondline of a free peel test is derived by considering the geometry shown in Figure 2.1. The forces and moments produced on a differential piece of the *flexible adherend* are assumed to equilibrate, yielding the following differential equation for the deflection of the flexible adherend *near the fracture point*:

$$\frac{d^4y}{dx^4}+\left(\frac{3E_2}{2E_1c^3a}\right)y=0 \tag{2.1}$$

in which

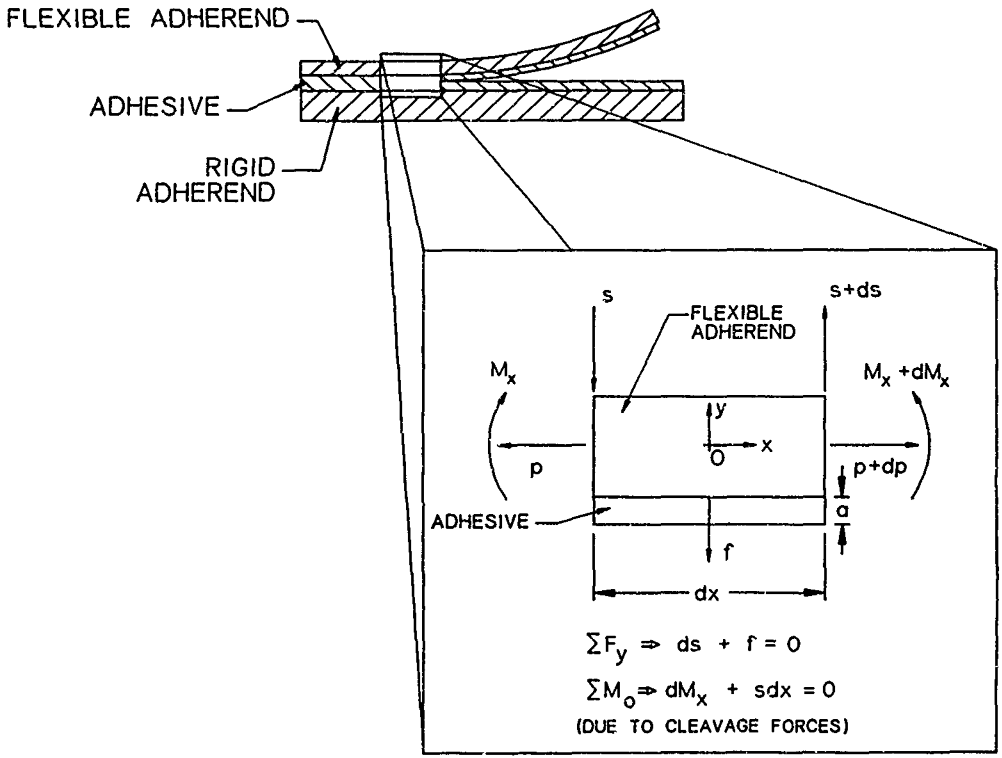


Figure 2.1. Free Peel Incremental Geometry [3].

y = deflection of flexible adherend still bonded to the rigid adherend

x = coordinate along the length of the specimen

E_2 = Young's modulus of the adhesive

E_1 = Young's modulus of the flexible adherend

c = half-thickness of the flexible adherend

a = thickness of the bondline

The assumptions are linear elastic material behavior for the adherend portion not yet debonded, and that the slope of the deflected adherend is small at the fracture point.

Solving this equation by traditional techniques and assuming that the resultant transverse shear force at the fracture point is negligible yields the following equation for the deflection of the adherend

$$y = \sqrt{\frac{3a}{2b^2c^3E_1E_2}}\ M_0\, e^{\beta x}\,(\cos\beta x + \sin\beta x) \tag{2.2}$$

in which

y = deflection of adherend still bonded to the adhesive

M_0 = moment produced in the flexible adherend at $x=0$

b = width of the flexible adherend

$$\beta = \sqrt[4]{\frac{3E_2}{8E_1c^3a}}$$

Since this equation is valid for $(-x)$ only, the maximum deflection occurs at $x=0$. The resulting maximum deflection is therefore given by

$$y_{max} = \sqrt{\frac{3aM_0^2}{2b^2c^3E_1E_2}} \tag{2.3}$$

To convert this deflection to stress, a simple 1-dimensional definition of strain is adopted:

$$\varepsilon = \frac{y}{a} \tag{2.4}$$

in which ε is the engineering strain. Using Hooke's Law, ($\sigma=E_2\varepsilon$), the maximum cleavage stress in the adhesive layer is given by

$$\sigma_{max} = \sqrt{\frac{3E_2}{2b^2ac^3E_1}}\, M_o \tag{2.5}$$

The moment, M_0, is the moment at x=0 caused by the loading of the flexible adherend during the test, and is simply the moment required to bend the adherend around the roller. The expression for the moment in an elastic/linear plastic adherend (modeled as a thin beam) in bending is given by

$$M_0 = b\left(1-\frac{E_y}{E_1}\right)\left[\sigma_y c^2 + \frac{2E_y c^3 \kappa}{3\left(1-\frac{E_y}{E_1}\right)} - \frac{\sigma_y^3}{3E_1^3\kappa^2}\right] \tag{2.6}$$

in which

b = width of flexible adherend

E_y = post-yield modulus of flexible adherend

σ_y = yield strength of flexible adherend

κ = curvature to which adherend is bending

Note that this equation is valid only if

$$\kappa > \frac{\sigma_y}{E_1 c} \tag{2.7}$$

This moment must be large enough that the maximum cleavage stress exceeds the stress required to propagate the crack *while the adherend remains conformed to the roller.* This means that the curvature in the equation for the moment (2.6) must be replaced by

$$\kappa = \frac{1}{(r+c)} \tag{2.8}$$

in which r is the radius of the roller.

The assumption that the crack will propagate when the cleavage stress exceeds the tensile strength of the adhesive yields the simple expression

$$\sigma_{max} > \sigma_0 \tag{2.9}$$

in which σ_o is the tensile strength of the bulk adhesive. Substituting the expression for the adherend moment (2.6) into the equation for σ_{max} (2.5), and the resulting expression into the above equation relating σ_{max} to σ_o (2.9) yields the following expression

$$\sigma_0 < \sqrt{\frac{3E_2}{2b^2 a c^3 E_1}} \left(b\sigma_y c^2 - \frac{b\sigma_y}{3E_1^2 \kappa^2} \right) \tag{2.10}$$

In this expression, the adherend is assumed to display elastic/perfectly plastic behavior ($E_y = 0$), which gave better results in [1]. Substituting $(1/(r+c))$ for κ and rearranging to factor out c yields

$$Ac^2 - Bc^{3/2} - c > D \tag{2.11}$$

in which

$$A = \sqrt{\frac{3E_2\sigma_y^2}{2aE_1}} - \sqrt{\frac{E_2}{6E_1a}}\left(\frac{\sigma_y^3}{E_1^2}\right) \tag{2.12}$$

$$B = \sigma_o \tag{2.13}$$

$$D = \sqrt{\frac{E_2}{6E_1a}}\left(\frac{\sigma_y^3 r^2}{E_1^2}\right) \tag{2.14}$$

The solution to (2.11), designated the *Maximum Cleavage Stress (MCS) Criterion*, yields the minimum adherend thickness which, by conforming to the radius of the roller, can generate the moment required to produce a cleavage stress in excess of σ_o. Note that the width of the specimen completely cancels out of the expression, as it should in a 1-D analysis.

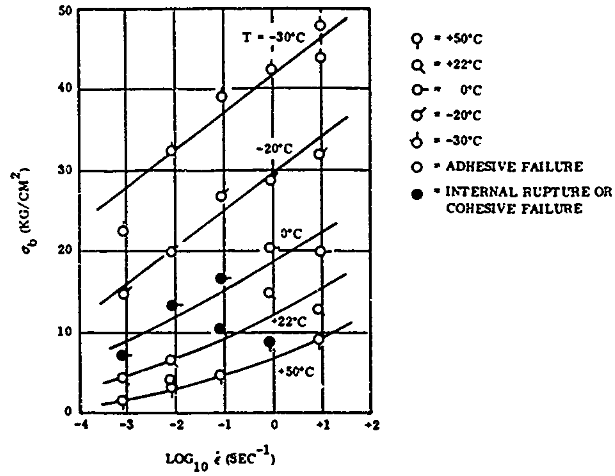
Since (2.11) is not a polynomial with integer powers, the equation must be solved for c by some numerical method. A combination Newton/Raphson - Bisection scheme was utilized in this study due to its simplicity. Other more efficient root solvers may be used.

Note that this equation can be readily applied to the Climbing Drum Test, since no assumptions have been made as to how the force which bends the adherend around the roller is introduced into the adherend. The only differences in the application to FRP and CDP test should be in the radius of the roller to which the adherend should conform.

2.2 Appropriate Values of Bulk Tensile Strength

The failure criterion being used in this analysis states that the adhesive crack will propagate when the cleavage stress exceeds the tensile strength of the bulk adhesive. Most manufacturer's data supplies approximate values for both stiffness and tensile strength that could readily be used in this analysis. However, these values were most likely obtained under test conditions different from those in the FRP or CDP test, namely highly different *strain rates*.

Data presented by Anderson et al. [4] and Gent [5] show significant increases in tensile breaking stress and free peel strength with increasing rate of extension and increasing peel rate, respectively. Strain rates for typical tensile tests (6 inch gage section, 0.01 in/min) cross-head rate) are in the range of 0.17 %/min. A first order kinematic analysis of an FRP specimen with a 0.01 inch glue line thickness (Appendix) shows a strain rate of 24.3%/min, if the test is conducted at a cross-head rate of 6 in/min as suggested by ASTM D3167-76. This represents an increase of two orders of magnitude in the strain rate at failure. Figure 2.2 indicates that increasing the strain rate to this degree approximately doubles the tensile breaking stress in a typical adhesive. This material behavior must be accounted for in the analysis, namely, by multiplying the bulk tensile strength by an appropriate rate correction factor.



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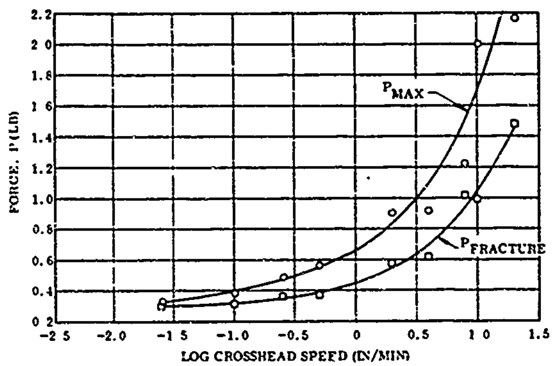

PEEL

Figure 2.2. Effect of Strain Rate on Tensile Strength and Peel Strength of a Typical Polyurethane Adhesive [4].

The specific effect of strain rate on tensile strength is most likely a material property that will vary from material to material. Therefore an empirical approach must be taken to suggesting appropriate rate correction factors for use in FRP and CDP tests. If this approach to predicting minimum thickness is correct, the appropriate factors should be in the range of 1.0 to 3.0, based on the work described in Reference 5. Section 4.5, which details test results, will discuss the strain rate factors and their influence on predicted minimum adherend thicknesses.

2.3 Validity of the Model's Assumptions

In closing the discussion of the minimum adherend thickness analysis, a contradiction which exists in the first order analysis presented in 2.1 and 2.2 must be acknowledged. If the moment produced by the flexible adherend is the only mechanism which induces the fracture to progress, the load required to run the test (the peel load) should be no greater than the load required to run an unbonded specimen (simply pulling a flexible adherend through the fixture). The reasoning is as follows. The moment in the unbonded specimen is reacted by the rear roller. In the bonded specimen, the reaction is shifted to the adhesive. In either case, however, the moment in the adherend should be the same since the adherend curvature is the same (that of the roller). Since the force on the adherend must produce the curvature, it would appear the force should be the same in both cases. Test results [1] show this conclusion to be incorrect. This contradiction, however, for a first order analysis, is recognized and accepted.

SECTION 3
CALCULATION OF FLEXIBLE ADHEREND DEFORMATION ENERGY IN A NON-CONFORMING FRP TEST

An analysis is now undertaken which will calculate the deformation energy in an adherend which does not conform to the roller.

3.1 Deformation Curvature of a Nonconforming Flexible Adherend

A flexible adherend which is not conforming to the roller, Figure 3.1, is essentially in a state of free peel from the point of debonding to the point where it reattaches to the roller. The geometry of the adherend can be specified by the single angle coordinate,ω, which is the angle from a line tangent to the point where the flexible adherend re-attaches to the roller to a line tangent to a given point on the flexible adherend. The angle ω ranges from 0 at the reattachment point to ω at the fracture point. Kaeble [2] derived an expression for the deformation curvature of an *elastic* adherend in free peel. Following his methodology, a similar expression can be derived for an elastic-linear plastic material.

The equation for the moment required to bend an elastic/linear plastic material to a given curvature κ was given in equation (2.6):

$$M = b\left(1-\frac{E_y}{E_1}\right)\left[\sigma_y c^2 + \frac{2E_y c^3\kappa}{3\left(1-\frac{E_y}{E_1}\right)} - \frac{\sigma_y^3}{3E_1^2\kappa^2}\right] \qquad (3.1)$$

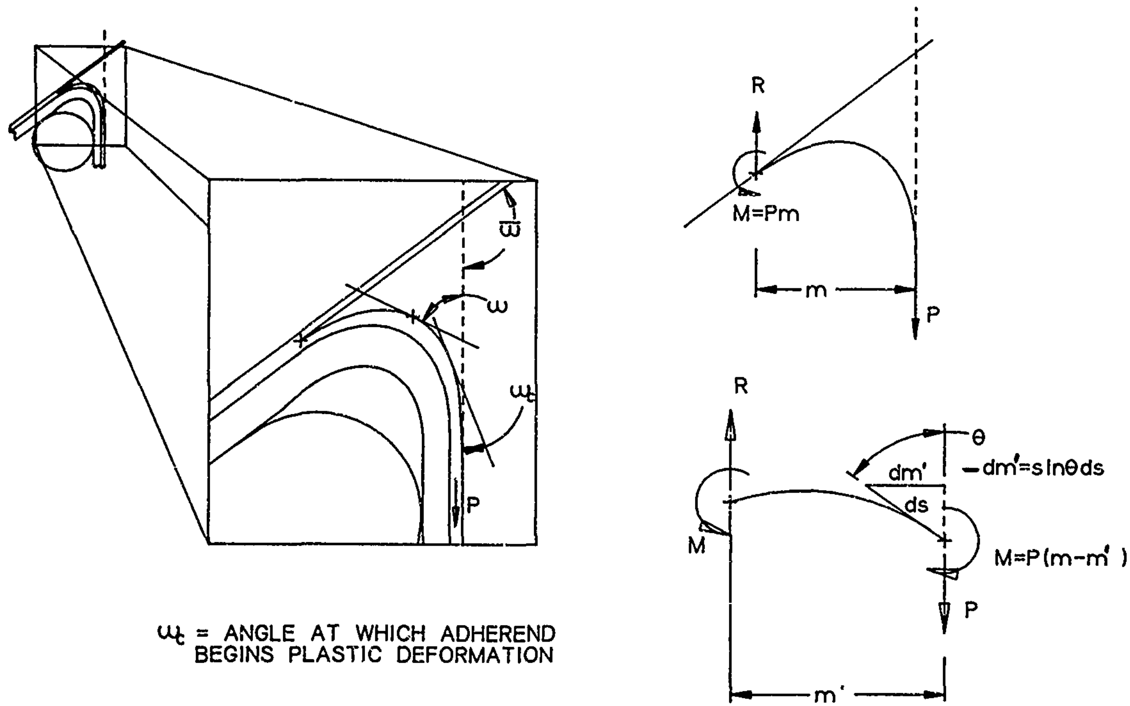

Figure 3.1. Nonconforming FRP Geometry.

Besides the test load applied during the running of the test, no other tractions or displacements are applied to the portion of the flexible adherend which does not conform, since it is not in contact with any other part of the test fixture. The moment applied at the debond point is simply

$$M_D = Pm$$

in which P is the test load applied to the adherend as the test proceeds and m is the "moment arm" from the debond point to the line through which the load acts. In order to calculate m, a free body diagram at some arbitrary angle θ (Figure 3.1) is constructed. The definition of curvature,

$$\kappa = \frac{d\theta}{ds} \tag{3.2}$$

in which s is the arc length along the flexible adherend, is substituted into equation (3.1), and M is replaced by P(m-m'). The resulting expression is

$$P(m-m') = b\left(1-\frac{E_y}{E_1}\right)\left[\sigma_y c^2 + \left(\frac{2E_y c^3}{3\left(1-\frac{E_y}{E_1}\right)}\right)\left(\frac{d\theta}{ds}\right) - \left(\frac{\sigma_y^3}{3E_1^2}\right)\left(\frac{d\theta}{ds}\right)^{-2}\right] \tag{3.3}$$

Taking the derivative of both sides with respect to s yields

$$-P\frac{dm'}{ds} = \frac{2E_y c^3}{3(1-E_y/E_1)}\frac{d}{ds}\left(\frac{d\theta}{ds}\right) + \frac{2\sigma_y^3}{3E_1^2}\left(\frac{d\theta}{ds}\right)^{-3}\frac{d}{ds}\left(\frac{d\theta}{ds}\right) \tag{3.4}$$

From Figure 3.1, dm'/ds= -sin θ. Making this substitution and multiplying both sides of (3.4) by dθ/ds yields

$$P\sin\theta\frac{d\theta}{ds} = \frac{2E_y c^3}{3(1-E_y/E_1)}\frac{d\theta}{ds}\frac{d}{ds}\left(\frac{d\theta}{ds}\right)+\frac{2\sigma_y^3}{3E_1^2}\left(\frac{d\theta}{ds}\right)^{-2}\frac{d}{ds}\left(\frac{d\theta}{ds}\right) \qquad (3.5)$$

Canceling the appropriate ds in the denominator of each term yields

$$P\sin\theta\, d\theta = \frac{2E_y c^3}{3(1-E_y)/E_1}\frac{d\theta}{ds}d\left(\frac{d\theta}{ds}\right)+\frac{2\sigma_y^3}{3E_1^2}\left(\frac{d\theta}{ds}\right)^{-2}d\left(\frac{d\theta}{ds}\right) \qquad (3.6)$$

The left side can be integrated from $\theta=\omega_c$ to $\theta=\omega$, in which ω_c is the largest angle at which the adherend is totally elastic, and θ is any angle along the length of the adherend up to the angle at the fracture point (same as the angle of reattachment). The right side terms are integrated from $d\theta/ds=\kappa_c$ to $d\theta/ds=\kappa$, in which κ_c is the largest curvature at which the adherend becomes totally elastic, and κ is the curvature corresponding to the angle ω. Carrying out the integration yields

$$P(\cos\omega_c-\cos\omega) = \frac{E_y c^3}{3(1-E_y/E_1)}\left(\kappa^2-\left(\frac{\sigma_y}{E_1 c}\right)^2\right)+\frac{4\sigma_y^3}{3E^2}\left(\frac{E_1 c}{\sigma_y}-\frac{1}{\kappa}\right) \qquad (3.7)$$

in which κ_c has been replaced by

$$\kappa_c = \frac{\sigma_y}{E_1 c} \qquad (3.8)$$

Equation (3.8) represents a simple expression for the largest curvature at which the adherend is totally elastic.

An expression for (cos ω_c) in (3.7) has been derived by Kaeble [2] and is given by

$$\cos\omega_c = 1 - \left(\frac{\sigma_y^2 bc}{3E_1 P}\right) \tag{3.9}$$

This expression can be derived by the methodology of equations (3.1-3.8) if the procedure is started with the expression for *elastic* bending in a beam (M/EI = dθ/ds, I = moment of inertia) instead of equation (3.1).

Substituting (3.9) into (3.7) and rearranging yields

$$\left[\frac{E_y c^3}{3(1-E_y/E_1)}\right]\kappa^3 - \left[\frac{E_y c}{3(1-E_y/E_1)}\frac{\sigma_y^2}{E_1} - \frac{4\sigma y^2 c}{3E_1^2} + P\left(1 - \frac{\sigma y^2 bc}{3E_1 P} - \cos\omega\right)\right]\kappa - \frac{4\sigma_y^3}{3E_1^2} = 0 \tag{3.10}$$

This yields an independent expression for the curvature of the adherend as a function of angle. The curvature at the debond point is given by substituting the angle at which the adherend re-attaches to the roller, $\bar{\omega}$, for ω in (3.10). The only other parameter needing to be specified is the load applied during the test. The expression can be solved for κ by any convenient means, including numerical root solvers (the method used in this study).

3.2 Numerical Approximation of Deformation Energy in the Flexible Adherend

With the curvature at the debond point known, the energy per unit length expended during the test can be calculated. For this first order analysis, the

load path of the adherend (the fact that the adherend expends additional elastic energy by straightening out after it has plastically deformed) is neglected. As a result, the strain energy calculated will be an *average* strain energy, averaged over the length of the adherend.

Equation (3.10) can be utilized to calculate the curvature at any point along the flexible adherend (given the angle ω at that point), in the range

$$\cos^{-1}\left(1-\frac{\sigma_y{}^2 bc}{3EP}\right)<\omega<\bar{\omega} \qquad (3.11)$$

($E=E_1$) which is the range in which the adherend has deformed plastically. The curvature for the portion which has deformed only elastically is given by [2]

$$\kappa_e=\sqrt{\frac{3P(1-\cos(\omega)}{Ebc^3}} \qquad (3.12)$$

and is valid in the range from $\omega=0$ to the beginning of the plastic range. The "e" subscript on κ refers to the fact that this curvature is the result of elastic deformation. The strain energy per unit length (u_p) associated with the curvatures in the plastically deformed region (assuming bending accounts for the majority of the energy) is given by

$$u_p = \frac{\sigma_y^3 b}{3E^2\kappa} + \frac{E_y \kappa^2 c^3 b}{3} + \sigma_y\left(1-\frac{E_y}{E}\right)\kappa c^2 b - \frac{\sigma_y^2\left(1-\frac{E_y}{E}\right)cb}{E} - \frac{E_y \sigma_y^3 b}{3E^3\kappa}$$

(3.13)

The strain energy per unit length (u_e) in the region which deforms only elastically is given by

$$u_e = \frac{Ec^3\kappa^2}{3} \tag{3.14}$$

In order to calculate the total strain energy, the strain energy per unit length must be added up (integrated) over both regions of the nonconforming length:

$$U = \int_{L_p} u_p \, ds + \int_{L_e} u_e \, ds \tag{3.15}$$

However, since u is in terms of ω instead of s, the following substitution (from the definition of curvature) is made:

$$ds = \frac{d\omega}{\kappa} \tag{3.16}$$

Substituting (3.16) into (3.15) yields a usable equation for calculating the total strain energy in the nonconformed portion of the adherend

$$U = \int_{0}^{\omega_c} \frac{u_e}{\kappa_e}\, d\omega + \int_{\kappa_c}^{\bar{\omega}} \frac{u_p}{\kappa_p}\, d\omega \tag{3.17}$$

The total length of the nonconformed adherend is calculated in a similar fashion, yielding

$$L = \int_{0}^{\omega_c} \frac{1}{\kappa_e}\, d\omega + \int_{\omega_c}^{\bar{\omega}} \frac{1}{\kappa_p}\, d\omega \tag{3.18}$$

in which L is the total length of the nonconformed adherend. The averaged energy per unit length, u), is then given by the simple expression

$$\bar{u} = \frac{U}{L} \tag{3.19}$$

Since the values of curvature for a given angle are calculated numerically, so must the average strain energy expressions (3.17-3.19) be evaluated numerically. Even if the closed form solutions for a cubic equation were used to solve (3.10) for κ, the resulting integral would be so complex that numerical techniques would still be required. In this study, Simpson's rule for numerically integrating a function was utilized.

SECTION 4
FRP TEST RESULTS AND DISCUSSION

A series of floating roller peel tests was conducted to establish the validity of, and confirm, minimum adherend thickness predictions from the maximum cleavage stress criterion. Because the strain rate dependence of the adhesives was unknown, the tests essentially were used to back calculate the correct strain rate factors. Factors around 2 were considered to establish the validity of the model. Parameters varied in the tests included adhesive strength and stiffness, adherend modulus and yield strength, glue line thickness, and adherend thickness.

4.1 Procedure

Tests were conducted according to ASTM D3167-76, with the exception that the UDRI fixture (Figure 1.5) was utilized instead of the ASTM fixture. This ensured that incorrect failures due to the specimen "flipping up" (Figure 1.3) would not occur. In addition, the front plate of the fixture was replaced with a 7/16-inch thick polycarbonate plate, which allowed observation of whether or not the adherend conformed to the roller during the test. A polar coordinate grid, with the origin at the center of the main roller (Figure 4.1), permitted measurement of the angle at which nonconforming adherends reattached to the roller. All tests were videotaped in order to make this measurement at a later time.

All tests were conducted at room temperature and humidity on an Instron Universal Test machine (model 1123) at a crosshead rate of 6 inches/min. Data

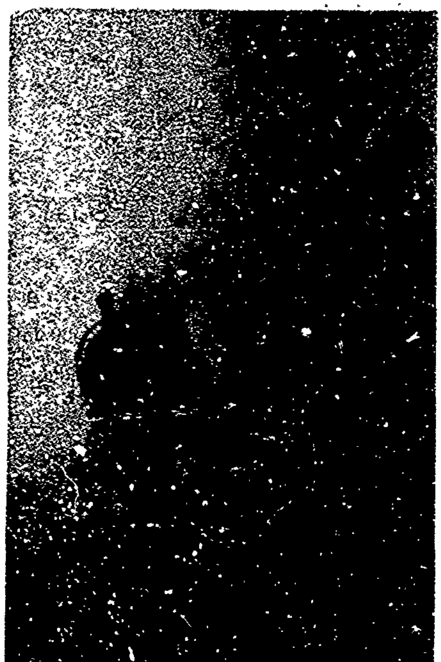

Figure 4.1. UDRI FRP Fixture with Polycarbonate Face Plate.

were collected via microcomputer with A/D capabilities, as well as on an autograph machine. Conformance of the adherend to the roller was noted visually. Measurements of the angle to re-conform to the roller were made by producing Polaroid photographs from still video images and measuring the angle with a protractor.

4.2 Test Matrix and Specimens

Table 4.1 shows the various adhesives and adherends used in the floating roller peel tests. Figure 4.2 displays the manner in which samples were numbered, in order to easily distinguish the characteristics of the sample. Two groups of tests were conducted. The first group (Set I) examined different yield strengths on the adherend material, with 6061-T6 aluminum (40,000 psi yield) and 3003-H14 aluminum (21,000 psi yield) serving as the two extremes. The second group (sets II and III) included variations in adhesive strength (5500 psi for EA 9330-3; 4400 psi for EA 9460), glue line thickness (~10 mil and ~15 mil), and modulus of the adherend (30,000,000 psi for steel, 10,000,000 psi for aluminum). Two values of adherend thickness were chosen in each set of tests, in order to obtain both conforming and nonconforming behavior.

Specimens were prepared according to the requirements of ASTM D 3167-76 and individual manufacturer's guidelines. Specimen preparation summaries are given in Table 4.2. In addition to the preparations listed, specimens labeled with "-10" and "-15" suffixes contained 8-10 mil and 12-15 mil glass beads, respectively, in order to control glue line thickness.

TABLE 4.1 FLOATING ROLLER PEEL TEST MATRIX

Spec. Set No.	Specimen Type	Adhesive Material	Adhesive E (psi)	Adhesive σ_y (psi)	Adhesive Avg. GLT (mils)	Adherend Material	Adherend E (psi)	Adherend σ_y (psi)	Adherend Thickness (mils)	No. of Spec.	Variables of Interest
I	396-020ALY-5	EA9396	350,000	8790	4.5 ± 0.6	AL 3003-H14	10,000,000	21,000	20	5	Adherend Yield Strenth
	396-040ALY-5	EA9396	350,000	8790	4.1 ± 0.6	AL 3003-H14	10,000,000	21,000	40	5	Adherend Thickness
	396-020AL-5	EA9396	350,000	8790	5.0 ± 0.6	AL 6061-T6	10,000,000	40,000	20	5	
	396-040AL-5	EA9396	350,000	8790	4.7 ± 0.4	AL 6061-T6	10,000,000	40,000	40	5	
II	330-024SS-10	EA9330.3	350,000	5500	8.6 ± 0.7	SS	30,000,000	35,000	24	5	Adhesive Strength
	460-024SS-10	EA9460	350,000	4400	8.1 ± 1.0	SS	30,000,000	35,000	24	5	Adherend Thickness
	330-048SS-10	EA9330.3	350,000	5500	8.5 ± 0.4	SS	30,000,000	35,000	48	5	Adherend Yield Strength
	460-048SS-10	EA9460	350,000	4400	8.5 ± 0.6	SS	30,000,000	35,000	48	5	Adherend Modulus Glue Line Thickness
III	330-020AL-10	EA9330.3	350,000	5500	6.9 ± 1.2	AL 6061-T6	10,000,000	40,000	20	5	Adhesive Strength
	460-020AL-10	EA9460	350,000	4400	8.4 ± 0.4	AL 6061-T6	10,000,000	40,000	20	5	Adherend Thickness
	330-040AL-10	EA9330.3	350,000	5500	6.5 ± 0.9	AL 6061-T6	10,000,000	40,000	40	5	Adherend Yield Strength
	460-040AL-10	EA9460	350,000	4400	8.3 ± 1.0	AL 6061-T6	10,000,000	40,000	40	5	Adherend Modulus Glue Line Thickness
II	330-024SS-15	EA9330.3	350,000	5500	15.0 ± 2.6	SS	30,000,000	35,000	24	5	Adhesive Strength
	460-024SS-15	EA9460	350,000	4400	11.1 ± 0.9	SS	30,000,000	35,000	24	5	Adherend Thickness
	330-048SS-15	EA9330.3	350,000	5500	13.5 ± 1.5	SS	30,000,000	35,000	48	5	Adherend Yield Strength
	460-048SS-15	EA9460	350,000	4400	12.4 ± 2.2	SS	30,000,000	35,000	48	5	Adherend Modulus Glue Line Thickness

TABLE 4.1. CONTINUED

Spec Set No.	Specimen Type	Adhesive				Adherend				# of Spec.	Variables of Interest
		Material	E (psi)	σ_y (psi)	Avg. GLT (mils)	Material	E (psi)	σ_y (psi)	Thickness (mils)		
III	330-020AL-15	EA9330.3	350,000	5500	14.4±1.5	AL6061-T6	10,000,000	40,000	20	5	Adhesive Strength
	460-020AL-15	EA9460	350,000	4400	14.6±1.5	AL6061-T6	10,000,000	40,000	20	5	Adherend Thickness
	330-040AL-15	EA9330.3	350,000	5500	13.1±2.7	AL6061-T6	10,000,000	40,000	40	5	Adherend Yield Strength
	460-040AL-15	EA9460	350,000	4400	13.3±1.2	AL 6061-T6	10,000,000	40,500	40	5	Adherend Modulus Glue Line Thickness

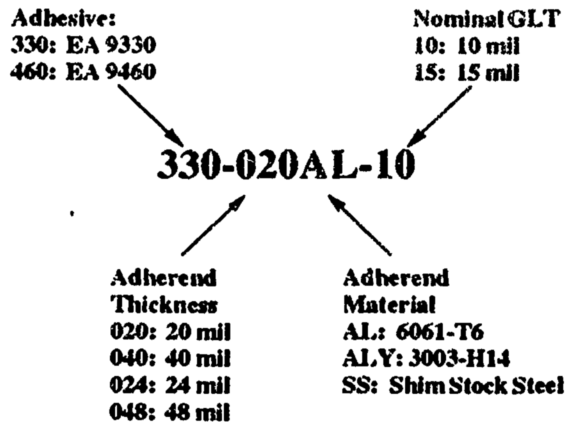

Figure 4.2. Specimen Numbering Scheme.

TABLE 4.2 FRP SPECIMEN PREPARATION SUMMARY

Sample Set	Surface Prep	Primer*	Adhesive Cure Cycle
I	Optimized FPL Etch (ASTM D2651, Method A)	BR127 - 30 min. air dry; cure 1 hr. @ 250°F	1 hr. @ 200°F
II	-steel grit blasted; 1 min. 10% HNO_3 etch; 1 min. H_2O rinse; hot air dry -aluminum phosphoric acid anodized (ASTM D3933)	BR127 on steel	1 hr. in press at 150°F and 18 psi
III	ASTM D3933	None	1 hr. in press at 150°F and 18 psi

* Primer applied to thickness of 0.0001-0.0003 inch.

4.3 Minimum Thickness Predictions and FRP Test Results

Table 4.3 shows the average minimum thickness predictions for each specimen configuration tested. Because the effect of strain rate on the apparent strength of the adhesives is not known, minimum thickness predictions are given for apparent adhesive strengths equal to bulk tensile strength, 2 times bulk tensile strength and 3 times bulk tensile strength. The values listed in Table 4.1 for adhesive bulk tensile strength in test sets II and III are "quasi-static" results given in the manufacturer's supplied data sheets. Values in test set I were determined by tensile testing of cast dogbone specimens at room temperature and humidity.

Table 4.3 also shows whether or not the adherend conformed to the roller during the test. For the purposes of verifying minimum thickness prediction, conformance is qualitatively noted as "did not conform," "intermittent conformity," or "fully conformed." More quantitative data are used in Section 4.5 to calculate the energy to deform non-conforming adherends. All cases in which the adherend did not conform or intermittantly conformed to the roller during the peel test consist of the behavior illustrated in Figure 1.4 since use of the UDRI-type test fixture eliminated the possibility of nonconformance of the type illustrated in Figure 1.3.

Table 4.4 displays the peel strengths obtained from FRP tests. The "Adherend Work" (energy to deform the adherend) was calculated using the procedure developed by Kemp [1]. The "% Work Adherend" is the percentage of the test load used to deform the adherend (recall the test load is equivalent to the total energy per unit length required to run the test). The "Adhesive Work" is the difference between Test Load and Adherend Work. "Apparent Peel Strength" is the adhesive work normalized by the width of the specimen. This

TABLE 4.3 FRP MINIMUM ADHEREND THICKNESS PREDICTIONS AND TEST RESULTS

Panel†	Adhesive	Additional Material	Adherend Thickness (inch)	Glue Line Thickness (inch)	Type of Conformity*	Predicted Minimum Adherend Thickness for a Critical Cleavage Stress of: **		
						σ	2σ	3σ
396-020ALY-5	EA 9396	3003-H14	0.020	0.026	A	0.018	0.074	-
396-040ALY-5	EA 9396	3003-H14	0.040	0.0045	B	0.033	0.126	-
396-020AL-5	EA 9396	6061-T6	0.020	0.0021	C	0.0083	0.017	-
396-040AL-5	EA 9396	6061-T6	0.040	0.011	C	0.0068	0.0094	-
330-020AL-10	EA 9330	6061-T6	0.020	0.0084	A	0.0076	0.0248	0.0550
330-040AL-10	EA 9330	6061-T6	0.040	0.0064	A	0.0064	0.0192	0.0421
330-020AL-15	EA 9330	6061-T6	0.020	0.0147	A	0.0116	0.0426	0.0955
330-040AL-15	EA 9330	6061-T6	0.040	0.128	A	0.0104	0.0373	0.0833
330-024SS-10	EA 9330	CR-SS	0.024	0.0088	B	0.0191	0.0761	0.1711
330-048SS-10	EA 9330	CR-SS	0.048	0.0085	A	0.0185	0.0738	0.1661
330-024SS-15	EA 9330	CR-SS	0.024	0.0151	A	0.0326	0.1302	0.2929
330-048SS-15	EA 9330	CR-SS	0.048	0.0132	A	0.0285	0.1138	0.2559
460-020AL-10	EA 9460	6061-T6	0.020	0.0083	A	0.0058	0.0161	0.0350
460-040AL-10	EA 9460	6061-T6	0.040	0.0084	C	0.0058	0.0162	0.0352
460-020AL-15	EA 9460	6061-T6	0.020	0.0154	A	0.0084	0.0288	0.0640
460-040AL-15	EA 9460	6061-T6	0.040	0.0135	C	0.0077	0.0254	0.0564
460-024SS-10	EA 9460	CR-SS	0.024	0.0087	A	0.0121	0.0482	0.1083

TABLE 4.3, CONTINUED

Panel†	Adhesive	Additional Material	Adherend Thickness (inch)	Glue Line Thickness (inch)	Type of Conformity*	Predicted Minimum Adherend Thickness for a Critical Cleavage Stress of: **		
						σ	2σ	3σ
460-024SS-15	EA 9460	CR-SS	0.024	0.0109	A	0.0152	0.0606	0.1362
460-048SS-15	EA 9460	CR-SS	0.048	0.0127	C	0.0177	0.0705	0.1586

† Each panel represents an average of 5 tests

* Type of Conformity:
  A = did not conform
  B = intermittently conformed
  C = fully conformed

** σ = bulk tensile strength obtained from manufacturer's literature or direct mechanical test

TABLE 4.4 FRP PEEL STRENGTH RESULTS*

Panel	Type of Conformity**	Test Load (lb)	Adherend Work (in-lb/in length)	Adhesive Work (in-lb/in length	% Work Adherend	Apparent† Peel Strength (lb/in width)	Failure Type***
396-020ALY-5	A	19.58	3.08	16.50	15.76	37.09	Y
396-040ALY-5	B	24.47	13.64	10.83	58.16	47.58	Y
396-020AL-5	C	5.96	4.18	1.78	72.60	11.30	Y
396-040AL-5	C	25.95	22.93	3.02	88.36	49.16	Y
330-020AL-10	A	23.66	2.65	21.01	11.20	66.14	X
330-040AL-10	A	43.62	15.27	28.35	35.01	81.29	X
330-020AL-15	A	40.95	4.37	36.58	10.67	68.58	X
330-040AL-15	A	59.21	19.70	39.51	33.27	87.82	X
330-024SS-10	B	12.16	6.78	5.38	55.76	11.27	X
330-048SS-10	A	66.12	25.50	40.62	38.57	94.05	X
330-024SS-15	A	29.71	6.67	23.04	22.45	49.24	X
330-048SS-15	A	65.57	28.62	36.95	43.65	76.36	X
460-020AL-10	A	15.88	3.22	12.66	20.33	31.62	X
460-040AL-15	C	32.56	20.39	12.17	62.62	25.95	X
460-024SS-10	A	17.99	5.33	12.66	29.63	33.89	X
460-048SS-10	C	33.28	21.57	11.71	64.81	31.95	X

* Each row represents an average of 5 tests.

** Type of Conformity: A = did not conform
B = intermittently conformed
C = fully conformed

*** Failure Type: X = cohesive within adhesive layer
Y = interfacial along adhesive/primer or adhesive/metal interface

† "Apparent" Peel Strength is the "True" peel strength if (a) flexible adherend conforms to roller
(b) failure is entirely cohesive (not along interface)

value should be unique for a given adhesive and glue line thickness, and should not vary among tests using different adherend thicknesses *if the tests conform to the roller.*

The results in Table 4.3 indicate several interesting trends. None of the EA 9330 specimens conformed to the roller. For these combinations of adherend material and adhesive, an adherend thickness greater than 0.040 inches is required to ensure the adherend conforms. For the aluminum adherends, the predicted minimum thicknesses agree with the requirement for critical cleavage stresses equal to approximately 2 to 3 times the bulk tensile strength listed in vendor data sheets for this adhesive. Since no specimen conformed to the roller, a precise value for critical cleavage stress is not possible. However, since the moment induced by the adherend increases with the cube of the thickness, it is reasonable that using a critical stress value of 3 will yield a correct minimum thickness. Alternatively, it is possible that the bulk tensile strength listed in the vendor data sheets may be somewhat inaccurate.

The EA 9330 specimens with steel adherends had higher minimum thickness predictions than those with aluminum adherends. Although this seems intuitively incorrect, it <u>is consistent</u> with the assumptions made in the model. A stiffer adherend will deflect less for a given moment. Since the stresses in the adhesive layer are based on the deflection of the adherend, a stiffer adherend results in less stress. Although the steel should intuitively generate a higher moment as it bends to the roller radius, the moment increase over aluminum is actually very small. The elastic/perfectly plastic assumption results in a moment that is strongly dependent on the yield strength, and for the radius of the roller used here, less dependent on modulus. Therefore, the small increase in elastic/plastic moment is overwhelmed by the large decrease in the elastic deflection. The net result is lower stress and a larger minimum thickness.

Another trend readily noted in Table 4.3 is the increase in minimum predicted thickness with increasing glue line thickness. From equation 2.10, the strain for a given deflection decreases with increasing glue line thickness. Since the stress is proportional to the one dimensional strain in the adhesive layer, increasing the glue line thickness also decreases the stress. This is reflected in equation 2.10, in which the stress in the adhesive layer varies inversely with the square root of the glue line thickness. To increase the stress to the critical stress level requires a thicker adherend.

All the EA9460 specimens followed a distinct pattern: specimens with the thinner adherends did not conform, while those with thicker adherends did. Comparing these trends in aluminum adherend specimens with the predicted minimum thicknesses shows the critical cleavage stress to be approximately 2 to 3 times bulk tensile strength as listed in vendor literature. The steel specimens show the critical cleavage stress to be slightly greater than 2 times bulk tensile strength for a 0.010 inch glue line, and slightly less than 2 times bulk tensile strength for a 0.010 inch glue line. This result qualitatively verifies that the Maximum Cleavage Stress Criterion can be used to predict minimum adherend thicknesses.

The data for EA9396 shows the critical stress to be between one and two times bulk tensile strength for the adherends of 3003-H14 aluminum. The specimens with 6061-T6 adherends conformed for both adherend thicknesses, although the failures appeared to occur between adherend and primer. While the failure mode is not ideal, the loads sustained represent a lower bound on adhesive failure load. The rate correction factor for these tests (EA 9396 tests) should therefore be lower than for the other tests, which all failed cohesively.

4.4 Apparent Peel Strength from FRP Test Results

In comparing specimens with the same adherend material and glue line thickness, the EA 9460 results show that most specimens with non-conforming adherends have higher apparent peel strengths than specimens with conforming adherends, because the adherend work in the nonconformed specimens has not been correctly calculated. The exception is the 15 mil glue line thickness steel specimens, on which the Apparent Peel Strengths of the conformed specimens are actually higher than nonconformed specimens. This is likely due to uncertainty in the properties of the steel (specifically, yield strength) and in whether or not the material is actually elastic/perfectly plastic. Note also that specimens with conforming adherends possess higher values in the "% Work Adherend" column. This fact again emphasizes that adherend work has not been correctly calculated in nonconforming specimens. The error consists in too little energy being computed from adherend deformation. This results in attributing too much energy into the breaking of the adhesive bond.

The high percentage of work that goes into deforming the adherend raises an interesting issue of precision and accuracy. Since the calculated peel strength is the difference between two numbers of similar magnitude (the peel load during the test and the calculated work to deform the adherend), a small uncertainty in either number may create a large uncertainty in the peel strength. This is one reason why a minimum thickness specification is critical. The adherend must be thick enough to enforce the correct failure mode, but as thin as possible so that as much energy as possible goes into fracturing the bond.

Finally, an examination of Table 4.4 indicates that specimens with the same adhesive and glueline thickness range do not in general show the same Apparent Peel Strength. This would seem to indicate a dependence on glueline thickness.

Although beyond the scope of this effort, it may be prudent in the future to carry out a more extensive test program to find a way to normalize Apparent Peel Strength calculations on the basis of glueline thickness.

4.5 Energy to Deform a Nonconforming Adherend and FRP Test Results

Using the methods of Sections 3.1 and 3.2, the energy to deform a non-conforming adherend can be calculated, and the apparent peel strength corrected for this additional energy. Figures 4.3 and 4.4 show typical still images taken from the video of nonconforming FRP adherends. Angles of reattachment were measured by a protractor and substituted into 3.10 to calculate the adherend curvature at the fracture point. The angle of reattachment and curvature at fracture were substituted into 3.19, and the additional energy to deform the adherend to the larger curvature was calculated.

Table 4.5 shows the additional work calculated for one sample from several of the groups which contained EA9330 or EA9460 adhesive. As the table shows, "% Work Adherend" increases for the EA9330 samples to levels more typical of conformed specimens, indicating the deformation energy has been more correctly accounted for. The "Apparent Peel Strength" also becomes more uniform. However, since none of the specimens conformed, no basis exists for knowing if the Apparent Peel Strengths represent values which would have been obtained if the specimens had conformed.

The EA9460 specimens, however, do indicate that, when the additional energy consumed by nonconforming adherends is accounted for, the Apparent Peel Strength is very close to that calculated for specimens which do conform. Again, the "% Work Adherend" column shows values close to those expected of conforming specimens. It is also interesting to note the close agreement

Figure 4.3. Nonconformance of a Specimen from Group 330-020AL-10.

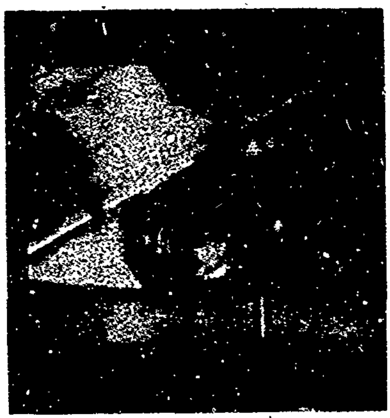

Figure 4.4. Nonconformance of a Specimen from Group 330-040AL-10.

TABLE 4.5

APPARENT PEEL STRENGTHS ACOUNTING FOR ADDITIONAL DEFORMATION ENERGY

Panel	Test Load (lb)	Adherend Work due to Deforming to Roller Curvature (lb-in/in)	Additional Work due to Greater Curvature in Nonconformance (lb-in/in)	Adhesive Work (lb-in/in)	% Work Adherend	Apparent Peel Strength (lb/in width)
330-020AL-10	23.66	2.65	6.0	15.01	37	47.2
330-040AL-10	43.62	15.27	9.6	18.75	43	40.0
330-048SS-10	66.12	25.50	18.24	22.38	66.1	51.7
330-024SS-15	29.71	6.67	5.7	17.34	42.0	37.0
330-048SS-15	65.57	28.62	15.0	21.95	66.5	45.34
460-024SS-10	17.99	5.33	5.37	7.29	59.5	19.4
460-020AL-10	15.88	3.22	4.52	8.14	50.0	19.80
460-040AL-10	24.05	17.03	0	7.02	70.81	17.90
460-020AL-15	21.06	4.43	4.50	12.13	42.4	25.86
460-040AL-15	32.56	20.39	0	12.17	62.6	25.95

between specimens with similar glue line thicknesses, indicating a possible relationship between glue line thickness and peel strength.

The measurement of the contact angle (angle at which the adherend reattaches to the roller) involves some judgement, as photographs of the test present some uncertainty as to where the adherend actually reattaches. Figure 4.5 indicates that an uncertainty of $\pm 10°$ at an angle of $90°$ (a typical contact angle) results in a change in Apparent Peel Strength of less than 5 lb/in. While on a percentage basis this is large, it represents an acceptable uncertainty in absolute terms.

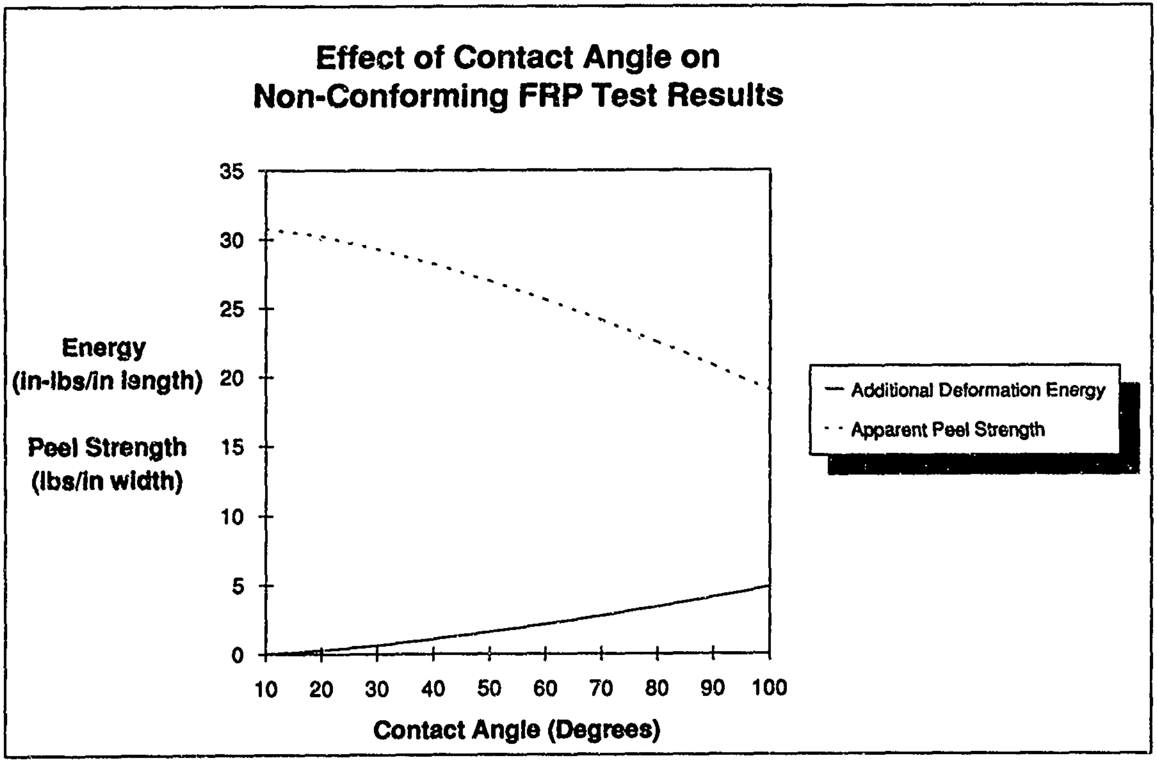

Figure 4.5. Effect of Contact Angle on Nonconforming FRP Results.

SECTION 5
ANALYSIS OF THE CLIMBING DRUM PEEL TEST

The analyses for the Floating Roller Peel test are now applied to the Climbing Drum Peel test. First, an expression which estimates the deformation energy in the CDP skin is presented. Use of this equation eliminates the need to run calibration specimens as required by ASTM D1781-76. Then, the Maximum Cleavage Stress Criterion will be applied to the CDP test in order to prescribe skin thicknesses which will prevent incorrect failure modes.

5.1 Estimation of the CDP Calibration Load

Kemp [1] produced an analysis which calculated the energy to deform the flexible adherend in an FRP test. Similarly in a CDP test, the adherend is permanently deformed, absorbing energy in the process. While the adherend deformation energy in an FRP test can be calculated in a tedious closed form solution or numerically as in [1], the adherend deformation energy in a CDP test is more easily computed because the flexible adherend does not straighten out as the test progresses. Therefore, load path changes accompanying load reversal (as in the FRP analysis of [1]) do not need to be accounted for. Although Kemp's numerical scheme [1] can perform this calculation, the lack of load reversal simplifies the analysis and leads to a straightforward expression for the skin deformation energy.

Figure 5.1 schematically depicts a calibration test in which an unbonded sample is tested. A simple energy balance yields the required force necessary to deform the adherend. The energy put into the system is merely the test force (F) moving through some distance (s_f):

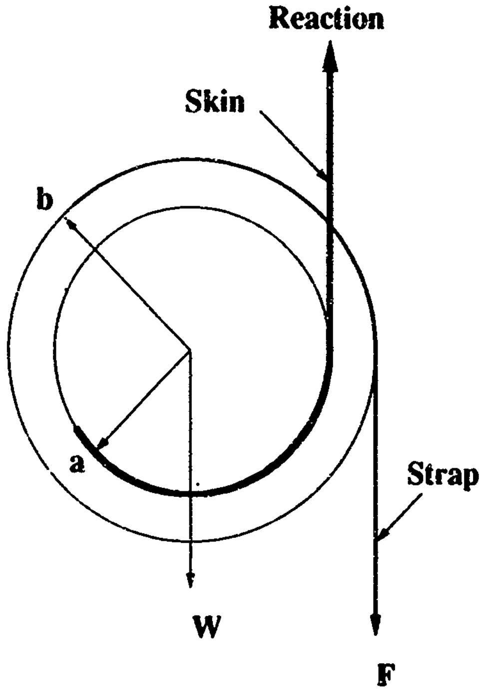

Figure 5.1. Free Body of Climbing Drum Peel Test.

$$E_{in} = Fs_f \tag{5.1}$$

Raising the drum and deforming the skin are the principal mechanisms which absorb the energy put into the system:

$$E_{absorbed} = Ws_W + \bar{E}s_W \tag{5.2}$$

Here W refers to the weight of the drum, s_w is the distance the drum is raised, and E is the energy per unit length to deform the adherend. Since the distance the drum is raised is equal to the length of adherend deformed, the term $E_{absorbed}$ refers to the total energy required to deform the adherend. Equating E_{in} to $E_{absorbed}$ and recognizing from the geometry that s_w is related to s_f by the factor $(r_a-r_b)/a$ yields the following expression for the force required to run the calibration test:

$$F = \frac{(W+\bar{E})r_a}{(r_b-r_a)} \tag{5.3}$$

As CDP results are reported in terms of torque, (5.3) can be expressed as the torque ($T_{adherend}$) required to deform the adherend and raise the drum:

$$T_{adherend} = (W + \bar{E})\, r_a \tag{5.4}$$

The energy per unit length to deform the skin around the drum is given by equation (3.13). When substituted in (5.3) or (5.4), the result yields an estimation of F or $T_{adherend}$ based on the material properties and thickness of the skin, and the weight and dimensions of the drum. For this application, the value

of curvature (κ) used should include the radius of the drum web and 1/2 the thickness of the skin.

5.2 Minimum Skin Thickness Predictions

The CDP test suffers from the same uncertainty problem as the FRP test: the deformation of the skin can account for a large percentage of the total energy absorbed by a bonded specimen. As a result, the calibration torque and test torque numbers can be relatively close. Subtraction of the two could result in large errors even if the errors in the two numbers are individually relatively small. Figure 5.2 illustrates this fact graphically, depicting uncertainties as high as 35% for 0.060-inch skins. A minimum thickness criterion would ensure the best possible trade-off between high uncertainties in thick adherends and incorrect failure modes in thin adherends.

The Maximum Cleavage Stress Criterion (2.11) is directly applicable to the CDP test for predicting minimum skin thicknesses. Several issues must be addressed in doing so, however. First, the curvature to which the adherend must conform is smaller than in the FRP test. As a result the strain rate may not affect the adhesive strength to the degree it did in FRP tests. Strain rate factors below 2 should be expected in CDP verification tests.

Second, the analysis may not correctly account for the effect of the adhesive in determining minimum thickness. Precise glueline thickness measurements are impossible in sandwich panels because of nonuniformity of the glueline and the presence of adhesive fillets on the walls of honeycomb cells. For this first order analysis, this possible source of error is neglected. A typical value of 0.010 in. is assumed for this effort.

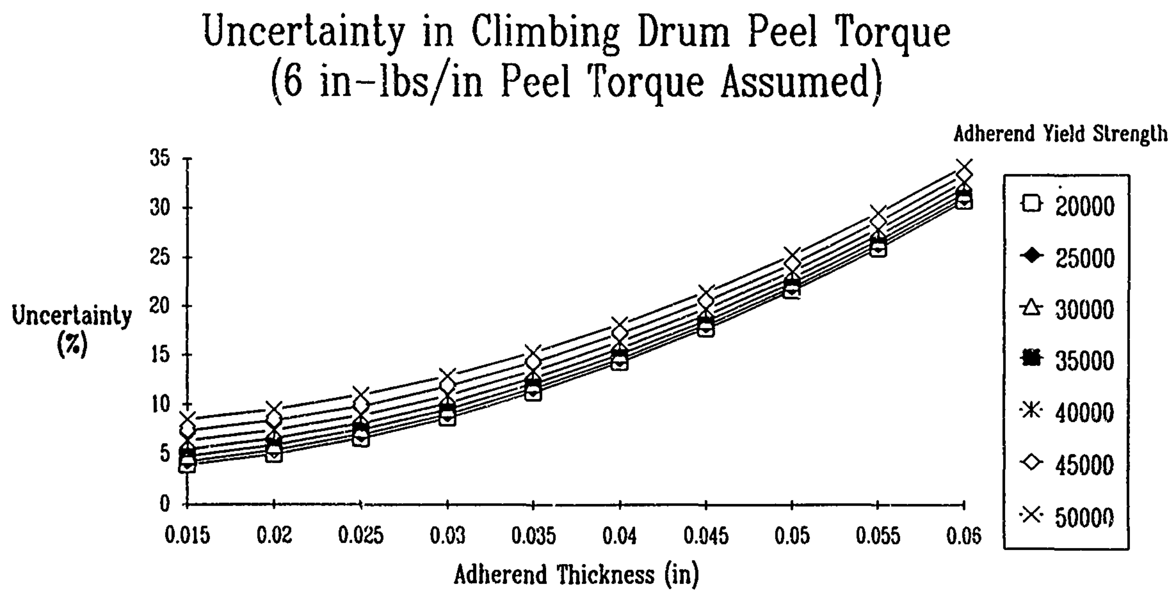

Figure 5.2. Uncertainty in CDP Torque.

Finally, adhesive is not distributed evenly across the face of the skin, since the glue adheres only to the edges of the cell walls. Due to this fact, it may seem that thin adherends (thinner than what would be expected if the entire skin surface area was adhering to the core)should be capable of maintaining conformance to the drum. However, very small regions exist at cell wall intersections where the adhesive may be considered to be uniformly distributed (Figure 5.3). To ensure skin conformance at these locations, the adhesive distribution can be considered uniform at all points across the adherend skin. However, this may result in prescribed thicknesses too large for non-uniformly distributed regions (and hence in higher uncertainty). Exchanging errors due to nonconformity for smaller errors due to higher uncertainty is considered desirable.

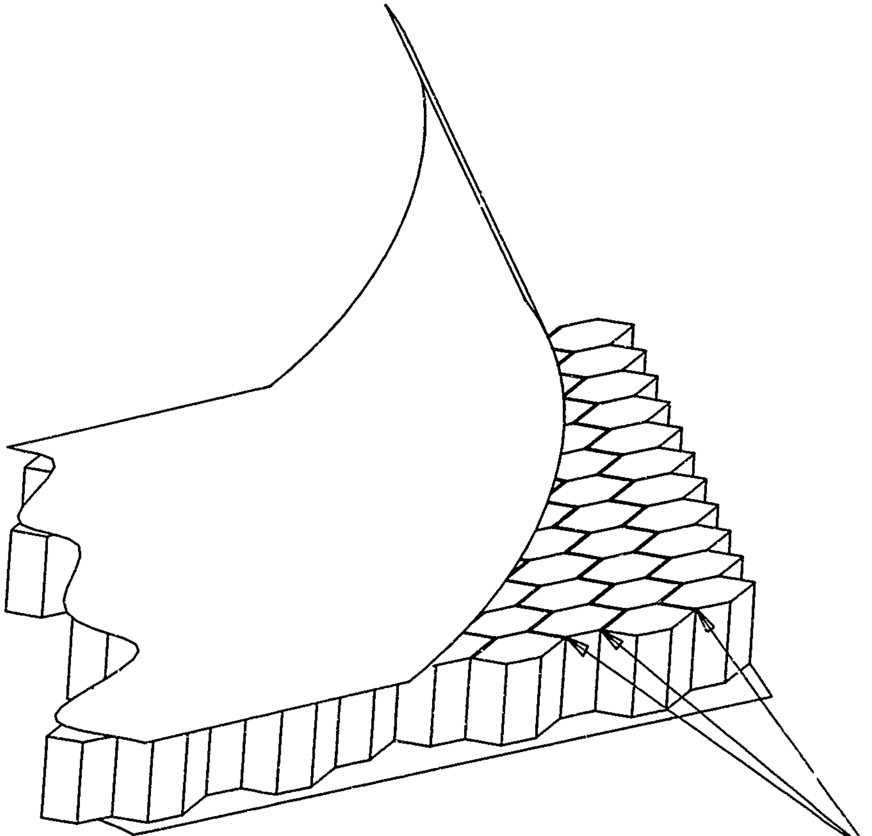

Figure 5.3. Regions of "Uniform" Adhesive Distribution in a CDP Specimen.

SECTION 6
CDP TEST RESULTS AND DISCUSSION

A series of climbing drum peel tests was conducted to establish the validity of both calibration load estimations and minimum adherend thickness predictions from the maximum cleavage stress criterion. Calibration load estimates should be within 5% to reduce uncertainty in the calculation of peel torque. Again, because the strain rate dependence of the adhesives was unknown, the tests essentially were used to back calculate the correct strain rate factors. Factors between 1 and 2 were considered to establish the validity of the model. Parameters varied in the tests included adhesive strength and stiffness and adherend thickness.

6.1 Procedure

Tests were conducted according to ASTM D1781-76. The drum diameters measured 2.00 in. for the web, and 2.49 in. for the flange. A 0.021-in.-thick strap was also utilized. All tests were conducted at room temperature and humidity on an Instron Universal Test machine (model 1123) at a crosshead rate of 6 inches/min. Data was collected via computer with A/D capabilities, as well as on an autograph machine. Peel loads reported represent an average of all data collected between the second and fifth inches of peeled skin length.

6.2 Test Matrix and Specimens

Table 6.1 shows the matrix for the honeycomb core specimens tested in climbing drum peel. Specimens were constructed using both thin and thick flexible adherends. Two adhesives were selected that were thought, based on

TABLE 6.1 CLIMBING DRUM PEEL TEST MATRIX (NUMBER OF TESTS)

Adhesive	2024-T3 (0.020 thick) Adherend	2024-T3 (0.040 thick) Adherend
Hysol EA 9628	3	3
American Cynamid FM300K	3	3
None	3	3

TABLE 6.2 CDP SPECIMEN PREPARATION SUMMARY

Adhesive	Skin Surface Prep	Primer	Vacuum Bag Cure Cycle
Hysol EA 9628	Phospheric Anodized (ASTM D3933)	None	Heat to 250°F for 1 hr @ 20" Hg vacuum
American Cyanamid FM 300K	Phosphoric Anodized (ASTM D3933)	None	Heat to 350°F for 1 hr @ 20" Hg vacuum

vendor data, to provide dissimilar peel strength levels. Three specimens were tested for each combination of adhesive and adherend thickness.

Specimens were prepared according to ASTM D1781-76 and individual manufacturer's guidelines. Core material consisted of 1-inch aluminum honeycomb with a nominal density of 7.9 PCF. Table 6.2 summarizes surface preparations and cure conditions for the 12 bonded sandwich samples.

6.3 Calibration Load Estimates and Test Results

Table 6.3 displays the results of the 6 CDP unbonded skins run for comparison to estimated adherend deformation energy (equation 5.3). For comparison purposes, the same calculation was made using the numerical technique of Kemp [1]. This was accomplished by neglecting the second and third "stages" of the deformation model in [1], in which the adherend (or skin in this case) travels around the roller and the load reverses, straightening out the adherend.

As shown, the closed form (equation 5.3) and numerical approximations slightly underestimate the force (within 5%) required to deform the 40 mil calibration adherend (in comparison to the experimental results), while overestimating (within 11%) the force required to deform the 20 mil adherend. This is considered good agreement. The closed form solution also gives consistently higher values of deformation energy than the numerical method. This is because the closed form solution considers only bending strain energy in its formulation, while the numerical scheme superimposes the measured force as an additional axial strain on the bending strain. Lower deformation energy (and hence force) results.

TABLE 6.3

CLIMBING DRUM PEEL CALIBRATION RESULTS

Sample	Material	Thickness	Measured Force to Deform Adherend (lb)	Force (lbs) Closed Form	Force (lbs) Numerical
1	2024-T3	0.040	102.5	99.85	97.20
2	2024-T3	0.040	102.4	99.85	97.20
3	2024-T3	0.040	101.3	99.85	97.20
4	2024-T3	0.020	33.28	36.81	36.50
5	2024-T3	0.020	33.38	36.81	36.50
6	2024-T3	0.020	33.65	36.81	36.50

Table 6.4 shows the torque required to fracture the adhesive in the 12 bonded honeycomb samples, based on the various methods of taking calibration loads (adherend deformation and drum weight) into account. On average, the closed form torque deviates from the measured torque by only 7%. This deviation is small enough to allow direct comparisons of peel torque between two adhesives, such as these, with apparently very similar peel strengths.

6.4 Minimum Skin Thickness Predictions and Test Results

The results of Table 6.4 show a discrepancy, as in the FRP test, between adherends of different thickness in torque required to fracture the adhesive. Ideally, the torque required to fracture the adhesive should be independent of the adherend thickness, since the use of calibration specimens, or calibration force calculations, accounts for the additional torque to deform the adherend. Table 6.4 also reveals a related fact: the calibration force accounts for roughly 75% of the measured force in bonded specimens with 0.040 inch skins, while it accounts for only 36% of the force in specimens with 0.020 inch skins.

Visual inspection of the test specimens with 0.020 inch adherends revealed "kinked" or "crimped" zones, Figure 6.1, which align with the regions between columns of cells. These regions possess a greater concentration of adhesive. The zones, appearing in reflected light as dark bands across the width of the adherend, are areas in which greater plastic deformation occurred. This increased deformation suggests that, at these points, the adherend pulled away from the climbing drum in order to transfer sufficient load to fracture the adhesive. The larger curvatures necessary to transfer sufficient load result in higher measured forces. As in the floating roller peel test, this behavior represents a different failure mode than in the specimens with thicker adherends

TABLE 6.4

CLIMBING DRUM PEEL STRENGTH RESULTS*

Adhesive	Adherend Thickness (in)	Measured Peel Force (lb)	Torque to Fracture Adhesive (in-lb/in)			Failure Mode
			Measured†	Closed Form††	Numerical††	
Hysol EA 9628	0.020	88.38	9.12	8.42	8.47	Cohesive
Hysol EA 9628	0.040	126.0	3.89	4.18	4.61	Cohesive
American Cyanamid FM300K	0.020	94.79	10.16	9.47	9.52	Cohesive
American Cyanamid FM300K	0.040	137.2	5.67	5.98	6.40	Cohesive

* Each row represents average of 3 tests

† Using measured Peel Force and an average of the 3 measured Calibration Forces (Table 6.3) for each thickness

†† Using measured peel force and Estimated Calibration Force (Table 6.3) for each adherend thickness

Figure 6.1. Crimped Zones in 20-mil CDP Specimens vs. Uncrimped 40-mil Specimens.

which remain conformed to the roller, and results in higher apparent peel strength.

The MCS Criteria for minimum adherend thickness, if valid, should predict the above results. Table 6.5 shows the predicted minimum thicknesses for the bonded CDP tests for a range of typical glueline thicknesses. Given that the sample glue-line thicknesses are generally between 0.007 and 0.010 inches, and the minimum adherend thickness is between 0.020 and 0.040 inches (since 0.040-inch specimens conformed while 0.020-inch specimens did not), the predictions are too low.

This is the same result seen in the FRP predictions. It would appear that strain rate may have some effect on the strength of the adhesive, as the CDP test is conducted at stroke rates similar to the FRP. However, since the CDP drum diameter is larger than the FRP roller diameter, the effect should be less pronounced in the CDP test. Table 6.5 shows this to be the case, as the required increase in adhesive strength is between 1 and 2 times. FRP tests showed this value to be between 2 and 3 times. These results validate the use of the MCS Criterion for predicting minimum adherend thickness to assure conformance to the drum.

6.5 Energy in Nonconforming Skins

Although it would be possible to calculate the additional energy expended in nonconforming CDP skins, this procedure was not implemented. A simple means for mounting a stationery grid (for angle measurements) to the test fixture could not be found in a timely manner. From visual inspection during the test, the distance the skin pulled away from the drum was very small compared to the non-conforming FRP adherends. Estimations of additional

TABLE 6.5

MINIMUM ADHEREND THICKNESS PREDICTIONS*

Adhesive	σ_o = Bulk Tensile Strength (psi)	GLT (in)	Minimum Adherend Thickness (in) for Adhesive Strength of: σ_o	$2\sigma_o$
EA 9639	7500	0.005	0.0158	0.0323
		0.007	0.0179	0.0421
		0.010	0.021	0.0574
		0.020	0.0320	0.170
FM 300K	5500	0.005	0.0134	0.0216
		0.007	0.0145	0.0263
		0.010	0.0161	0.0338
		0.020	0.0216	0.0605

* 2024-T3 aluminum skins

deformation energy without the benefit of a reference grid would be difficult. A means for making angle measurements needs to be developed before accurate data can be obtained.

SECTION 7
CONCLUSIONS AND RECOMMENDATIONS

The following conclusions are made:

- The Maximum Cleavage Stress Criterion, as a first order estimate, appears to reasonably predict the minimum flexible adherend thickness in FRP and CDP tests if strain rate effects are accounted for. The predicted thicknesses are particularly sensitive to the glueline thickness and strength of the adhesive, and to the yield strength of the adherend material.

- The bulk tensile strength of the adhesive utilized in the calculations appears, from the literature, to be highly dependent on strain rate. Since manufacturer's data consists of data derived from quasi-static tests, and FRP and CDP tests are run considerably faster, the tensile strengths used in minimum thickness calculations need to be increased. Factors in this study range from just over 1 to 3 times. Values of this magnitude agree with strength increases reported in the literature.

- The additional energy consumed by adherends which do not conform may be calculated in order to compare peel strengths with adherends which do. However, results may still differ slightly since failure modes are slightly different. In addition, this calculation requires collection of additional data to measure the geometry of the nonconforming adherend. This may not be desirable in some cases.

- The "% Work" of the adherend can be used as a diagnostic tool to determine if adherends are indeed conforming. Adherend deformation accounts for 60-75% of the test load measured in a bonded sample if the

adherend has conformed. If it has not, the adherend will appear to account for less energy, 20-50%.

- The calibration loads in a CDP test can be accurately calculated (to within an average of 7% for the adherends tested in this study) with a simple equation, eliminating the need for the testing of dummy samples.

- CDP results suggest that the 20-mil adherend thickness suggested by ASTM D1781-76 is inappropriate for higher peel strength adhesives. For instance, a low strength adhesive (or high strength adhesive which becomes low strength at elevated temperature) may result in a CDP test in which a 20-mil adherend does conform to the drum. Comparison to higher strength adhesives (or the same adhesive at room temperature) would not be possible because adherend work in the higher strength test would not be correctly calculated.

The following recommendations are made:

- Investigate glue line effects of both FRP and CDP core samples.

- Experimentally investigate the behavior of CDP and FRP tests at other temperatures. Validate that the temperature effects on minimum thickness predictions can be based solely on changes in the material properties of adhesive and adherend.

- Investigate a wide array of typical adhesives to find out if the strain rate effect is consistent from adhesive to adhesive for FRP and CDP tests. Correlate these results to a battery of tensile tests which determine the effect of strain rate on tensile properties.

- An alternative approach may be developed to predict minimum adherend thicknesses based on peel strength of the adhesive rather than bulk tensile strength and strain rate effects. Although the criterion would require knowing the peel strength of the material before the peel test is conducted, it may be possible to develop a criterion in which uncertainty in minimum adherend thickness is affected only slightly by uncertainty in peel strength. In that case, the criterion would require only a ball-park estimate of peel strength in order to adequately predict minimum thickness.

- Changes should be made in ASTM D3167 and D1781 that address the question of adherend nonconformance to the roller or drum and what adjustments in specimen design should be undertaken to correct nonconformance.

- Changes should be made in ASTM D3167 data reduction procedures to account for adherend energy absorption and to report a more "pure" adhesive peel strength.

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Appendix

Strain Rate Approximation for Floating Roller and Climbing Drum Peel Tests

The strain rate of the adhesive layer in a Floating Roller Peel (FRP) or Climbing Drum Peel (CDP) test can be estimated from a first order kinematic analysis. Figure A1 depicts a flexible adherend conforming to a "generic" roller (it is irrelevant whether the roller is from an FRP or a drum from a CDP test). The adhesive is assumed to stretch as the adherend progresses around the roller. The displacement in the adhesive (u) is given by

$$u = h - h_o = R + c - (R + c)\cos\theta \qquad \text{(A.1)}$$

The strain (ε) is given by

$$\varepsilon = \frac{h - h_o}{h} = \frac{(R+c)}{h}(1 - \cos\theta) \qquad \text{(A.2)}$$

Taking a derivative to get the strain rate ($\dot{\varepsilon}$) yields

$$\dot{\varepsilon} = \left(\frac{R+c}{h}\right)\sin\theta\,\dot{\theta} \qquad \text{(A.3)}$$

The term $(R+c)\dot{\theta}$ can be rewritten in terms of the velocity (crosshead speed) of the peel test

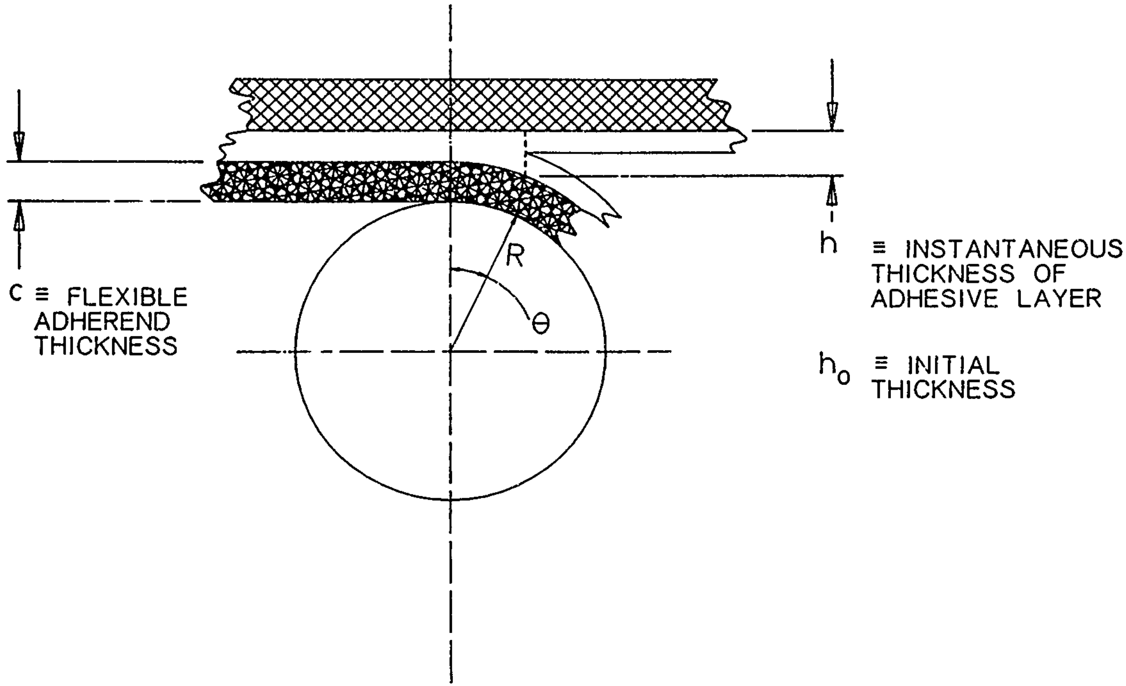

Figure A1. Geometry for Strain Rate Approximation.

$$(R+c)\dot{\theta} = V\frac{(2(r+c))}{2r+c} = V_{AD} \qquad (A.4)$$

in which V is the velocity of the peel test (velocity of the adherend midplane) and V_{AD} is the velocity of the adhesive (velocity of the adhesive/adherend interface). Substituting Equation A.4 into A.3 shows the strain rate to be a sample function of the test velocity and angle at which the adhesive breaks:

$$\dot{\varepsilon} = \frac{V_{AD}}{h}\sin\theta \qquad (A.5)$$

For $\theta \ll 1$, $\sin\theta \approx \theta$. Equation A.5 becomes

$$\dot{\varepsilon} = \frac{V_{AD}\theta}{h} \qquad (A.6)$$

Finally, we recognize that θ can be expressed as a function of V_{AD}:

$$\theta = \frac{V_{AD}}{(r+c)}\,t \qquad (A.7)$$

in which t is time. Substituting Equation A.7 into A.6 yields

$$\dot{\varepsilon} = \frac{V_{AD}^2\,t}{h(r+c)} \qquad (A.8)$$

Equation A.8 can now be used to find t at the point where the adhesive fails. To do this, Equation A.8 is integrated, resulting in an expression for t as a function of ε_u:

$$t = \sqrt{\frac{2\varepsilon_u h(r+c)}{V_{AD}^2}} \tag{A.9}$$

in which ε_u is the strain to failure of the adhesive. For this study, ε_u was determined by assuming the adhesive is linear to failure:

$$\varepsilon_u = \frac{\sigma_o}{E} \tag{A.10}$$

in which σ_o is the adhesive's bulk tensile strength, and E is the modulus of the adhesive. The value of t from Equation A.9 can then be substituted into A.8 to arrive at a value of strain rate at failure of the adhesive.

Some typical values for the Floating Roller Peel Test are as follows:

σ_o = 5500 psi

E = 350,000 psi

h = 0.01 in

r = 0.531 in

c = 0.02 in

V = 6 in/min = 0.1 in/sec (V_{AD}=0.1018 in/sec)

Substituting into Equation A.9 yields

t = 0.1293 sec.

Substituting into Equation A.10 yields

$\dot{\varepsilon}$ = 0.243 in/in/sec = 24.3%/sec

The resulting strain rate is exceptionally high compared to a quasistatic test, in which the strain rate is nominally 0.8 %/sec.

Some other comments and observations:

- $\dot{\varepsilon}$ varies with $1/h$. Doubling the adhesive thickness reduces $\dot{\varepsilon}$ by a factor of 2.
- $\dot{\varepsilon}$ varies with $1/(R+c)$. Since $c \ll R$, increasing adherend thickness does not change $\dot{\varepsilon}$ significantly. For example, $c = 0.04$ yields $\dot{\varepsilon}$ = 23.9%/sec.
- The effect may be more noticeable between specimens with like adherends and different GLT's than with specimens of different adherends and similar GLT's.
- Assuming the adhesive linear to failure is a <u>conservative</u> estimate; increasing ε at failure, as in a material which may deform viscoelastically, increases t and hence $\dot{\varepsilon}$.

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